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A Straightforward Approach for Cost-Effective Mitigation of Vehicle Interior Sound Leakage Noise and Structural Resonances

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Abstract

A novel and cost-effective methodology for vehicle NVH (Noise, Vibration, and Harshness) optimization is proposed to efficiently detect and mitigate interior noise sources. This approach eliminates the need for visual scanning and other time-consuming conventional methods typically used in the sound leakage detection process. The technique is structured in three key stages. First, the leakage detection and mapping stage employs a single P–U (Pressure–Particle Velocity) probe to perform detailed sound intensity measurements, generating high-resolution acoustic color maps that accurately localize leakage paths and structural transmission zones across the vehicle body. In the second stage, acoustic treatment, sound-absorbing materials are strategically applied to the identified critical regions, ensuring optimal resource utilization in terms of cost, weight, and acoustic performance. Finally, the performance evaluation stage quantifies the effectiveness of the applied treatments by comparing key acoustic indicators—particularly the Sound Pressure Level (SPL)—before and after the intervention. Experimental results demonstrate that the proposed method achieved a 3 dB reduction in SPL for front passengers and an average 1 dB reduction for rear passengers, confirming its effectiveness in improving overall cabin acoustic comfort. This streamlined methodology provides a practical, repeatable, and efficient alternative to complex conventional NVH diagnostic procedures, facilitating faster and more cost-effective vehicle development and refinement.

Keywords: sound intensity; acoustic leakage detection; interior noise; NVH optimization.

1. Introduction

Vehicle interior noise is a critical determinant of perceived quality and passenger comfort, making NVH performance a primary focus in automotive design, a challenge further emphasized in electric vehicles where masking engine noise is absent [1]. The vehicle sound package—comprising materials for absorption, insulation, and sealing—is fundamental for controlling noise transmission into the cabin [2]. While numerical simulation techniques like Statistical Energy Analysis (SEA) are established tools for sound package development, their accuracy is often constrained by a heavy reliance on precise material characterization and an inability to perfectly model real-world assembly details, which can lead to significant prediction errors [3, 4]. Although recent data-driven approaches show promise in alleviating some of these shortcomings, they still depend on extensive datasets and complex configurations [5]. Consequently, there is a persistent need for streamlined, experimentally driven methodologies that can efficiently and accurately identify acoustic leakage paths to enable targeted and cost-effective sound package optimization.

The evolution of vehicle NVH optimization has seen a clear trajectory from basic vibration analysis towards sophisticated acoustic measurement techniques. The field was advanced by acoustic imaging, which revealed the limitations of correlating structural vibration with sound radiation [6]. A pivotal development was the Pressure-Particle Velocity (P-U) probe, valued for its near-field sensitivity and directivity in complex acoustic environments [7]. This technology was rapidly adopted for Panel Noise Contribution Analysis (PNCA), with methodologies evolving from initial multi-probe arrays [8] to faster, high-resolution techniques [9] and their application in electric vehicles [10]. Further refinements led to comprehensive 3D sound intensity scanning for interior mapping [11], with applications expanding to structural damping [12] and harsh industrial settings [13]. The most recent innovations involve hybrid approaches that combine experimental sound intensity data with numerical simulation for predictive modelling [14, 15], merging rapid experimental characterization with virtual prototyping.

Despite its advantages, the acoustic visualization method possesses notable limitations. Its accuracy in pinpointing sound leakage direction can be compromised in highly reflective environments like vehicle interiors, where reflections may be misinterpreted as primary noise sources. This can lead to ambiguous results and requires significant operator expertise for correct interpretation.

Another prominent experimental methodology is Transfer Path Analysis (TPA), a family of techniques designed to quantify the contribution of individual vibration paths from a source to a receiver. This method is powerful for diagnosing structure-borne noise issues by breaking down the total vibration into its constituent paths [16]. Recent advancements continue to refine this approach, including Inverse TPA for faster assessments [17] and time-domain TPA for diagnosing transient events like door slams [18]. Recent data-driven approaches are being integrated with TPA to automate path identification, improve robustness to noisy measurements, and enable faster, more accurate ranking of dominant transmission paths from large sensor arrays [19, 20].

However, while TPA is highly effective at identifying and ranking the significance of specific structural transmission paths, it possesses inherent limitations for the task of rapid leakage localization. The method is notably sophisticated, requiring extensive sensor instrumentation on multiple attachment points, which makes it a time-consuming and complex process. Crucially, TPA identifies the paths of energy transfer (e.g., through specific mounts or structural connections) but does not directly visualize or map the spatial areas on the vehicle body where acoustic leakage is occurring. Consequently, while invaluable for solving structure-borne problems, it is less suited for the efficient, broad-area scanning required to pinpoint airborne leakage zones and structural radiation areas.

In addition to instrumental techniques, subjective assessment methods are sometimes employed for initial noise detection. These approaches typically involve creating an excitation inside the vehicle, often with an internal sound source, and attempting to localize leaks through auditory cues using devices like medical stethoscopes or simply by occupant perception during a drive. While these methods offer a low-cost and immediate starting point, they are characterized by significant limitations that restrict their utility for precise engineering refinement. The human ear struggles to localize sound direction accurately in a reflective vehicle cabin, and these methods yield only qualitative, non-comparable results, lacking the quantitative data required for effective NVH optimization.

Given the limitations of existing methods—including the complexity of simulations, the qualitative nature of acoustic visualization, the path-based focus of TPA, and the subjectivity of basic auditory checks—a clear need exists for a streamlined, quantitative, and spatially accurate diagnostic technique. To address this gap, this study aims to develop a simplified, experimentally driven framework.

This study presents a streamlined experimental framework for identifying and mitigating vehicle cabin sound leakage through integrated P-U probe measurements, acoustic color mapping, and quantitative treatment evaluation. The methodology offers three key advantages: operational efficiency through single-probe scanning that reduces sensor requirements and testing time; objective visualization via high-resolution acoustic maps that enable direct comparison and prioritization of leakage areas; and enhanced accuracy through the P-U sensor's inherent directionality, which minimizes measurement ambiguity in reflective environments for precise source localization.

The structure of this article is organized as follows:

- Section 2 presents the proposed methodology and experimental procedure, detailing the setup, measurement process, and sound package evaluation.
- Section 3 discusses the results and provides an in-depth analysis of the acoustic color maps and post-treatment performance.
- Section 4 concludes the study, summarizing key findings and highlighting directions for future research and practical implementation.

2. Proposed Methodology and Experimental Procedure

2.1 Experimental Setup

To identify acoustic leakage paths and weak transmission zones within the vehicle cabin, a controlled experimental setup was developed. A broadband artificial noise source was employed as the excitation signal. The sound generator was positioned at the geometric center of the cabin and oriented toward the dashboard to replicate the propagation path of exterior the airborne noise generated by the engine and other systems located in the engine compartment. This configuration ensures a dominant and well-defined acoustic field, effectively minimizing interference from unintended transmission routes such as hidden leaks or structural gaps.

Accurate sound leakage detection requires that the acoustic excitation originate from within the cabin. If the sound source were placed externally, reflections and the complex structure of the vehicle body would make precise localization of openings impossible. Therefore, the chosen internal excitation approach provides superior control and spatial resolution for mapping transmission paths.

Figure 1 shows how to facilitate accurate near-field measurements, components obstructing access to the firewall region—such as the engine, gearbox, and radiator—were temporarily removed. However, all structural and acoustic boundary elements directly interfacing with the firewall (e.g., wiring grommets, HVAC ducts, and steering column passages) were retained to maintain realistic boundary conditions representative of operational scenarios. This ensured that the measurement results accurately reflect the true sound transmission behavior of the cabin structure.

Figure 1. Engine compartment after removing some components.

Following the identification of primary leakage points, targeted countermeasures were implemented using specifically selected sound-absorbing and sealing materials applied to critical areas. Material selection prioritized acoustic absorption efficiency in the 500–4000 Hz range and ease of integration with vehicle components. The treatment combined polyurethane (PU) foam for broadband mid-to-high frequency absorption [21] and ethylene propylene diene monomer (EPDM) rubber for damping and airtight sealing [22]. This dual-material approach ensured balanced performance in absorption, vibration damping, and structural sealing, leading to measurable cabin acoustic improvement.

2.2 Comparative Metrics Evaluation Procedure

After implementing the sound package, a follow-up interior noise test was conducted to evaluate the effectiveness of the applied treatments. The same test conditions used during the baseline measurements were maintained to ensure data consistency.

The acquired data were processed in the frequency domain to assess reductions in SPL. These indicators quantify the improvement in perceived passenger comfort and the overall acoustic performance of the cabin after the application of the sound package.

By comparing pre- and post-treatment acoustic maps, the efficiency sound packaging material and its placement could be directly evaluated. This iterative approach—comprising leakage detection, sound package implementation, and quantitative verification—provides a systematic and cost-effective methodology for optimizing interior noise performance, as shown in the Fig. 2 flowchart.

The flowchart outlines the step-by-step experimental framework consisting of three main stages: First, Problem Detection involves controlled acoustic excitation inside the vehicle cabin followed by sound intensity scanning using a PU probe to generate high-resolution acoustic color maps. These maps are then analyzed to identify acoustic leakage paths and structural resonances. In the second stage, targeted acoustic treatment, absorbing materials are selectively applied to the identified critical areas to address noise transmission paths. Finally, the Post-Treatment Evaluation stage performs comparative noise measurements before and after treatment to assess the effectiveness of the applied insulation. If a significant noise reduction is not achieved, the process is iteratively refined. This methodology ensures a systematic, resource-efficient, and data-driven approach to optimizing cabin acoustics.

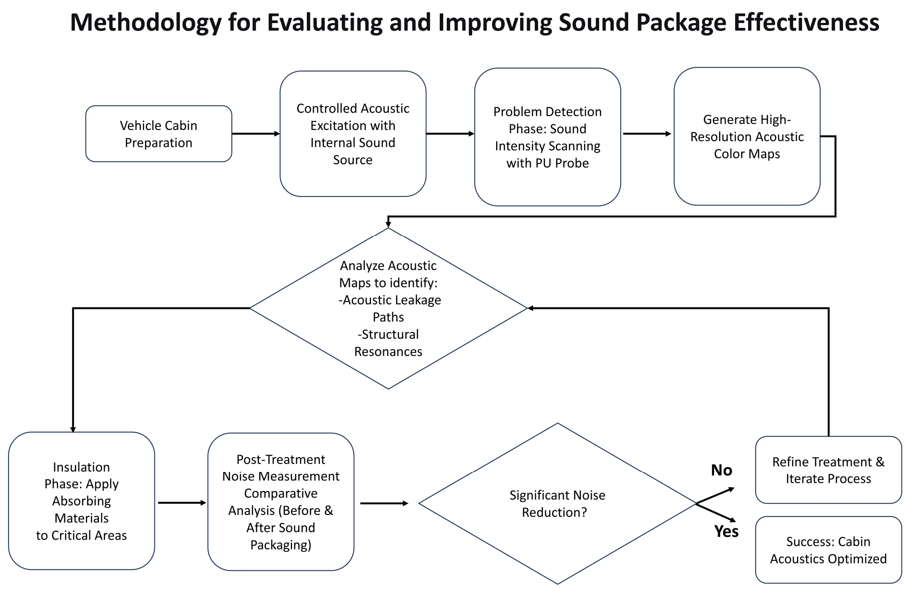


Figure 2. Sound acoustic absorption materials.

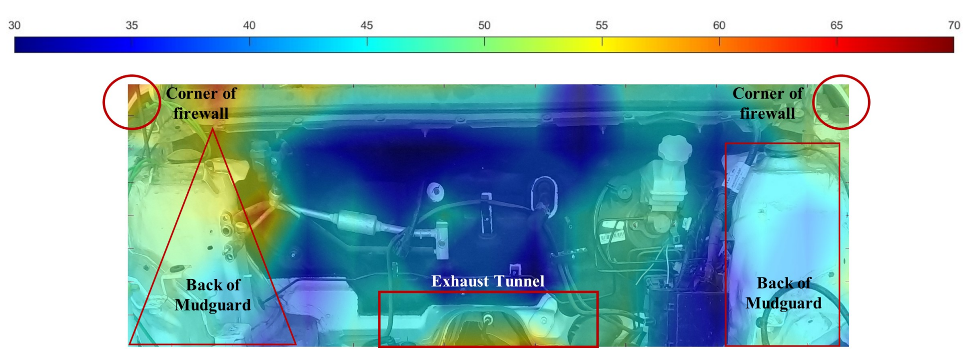
3. Results and Discussion

Figure 3 presents a comparative sound intensity map of the vehicle's firewall, excited by a 2kHz sine wave, before and after the application of the targeted sound package. A total of 85 measurement points were precisely assessed using a P–U sensor to capture the acoustic response. The baseline measurement (Figure 3a) clearly reveals that the right side of the firewall exhibits a significantly higher concentration of high-intensity zones (red) compared to the left (driver's) side, indicating pronounced acoustic leakage. Three critical regions were consistently identified as primary leakage paths:

1. The corners of the firewall, particularly on the right side.
2. The exhaust tunnel.
3. The back of mudguard.

These regions demonstrated relatively high noise transmission, indicating weak acoustic insulation or small structural openings.

Following the treatment, the results in Figure 3b show a substantial reduction in sound intensity levels across all previously identified critical regions, visually confirming the efficacy of the installed insulation.



(a)

(b)

Figure 3. Sound intensity maps of the vehicle firewall under 2 kHz excitation: (a) before treatment, showing critical leakage paths; (b) after sound package application, demonstrating significant noise reduction.

Subsequently, a comprehensive interior noise evaluation was performed to assess the effectiveness of the applied sound package under identical excitation conditions. The interior SPL was measured simultaneously at multiple passenger seating positions to capture the overall cabin acoustic response during two distinct operating conditions: Run-Up and Coast-Down tests.

Figure 4 presents the Run-Up test results, which represent the condition where the vehicle engine speed is gradually increased under load. This test highlights how the cabin acoustic response behaves as the engine and drivetrain components generate increasing excitation forces. Following the application of the targeted sound insulation treatment, a noticeable improvement was observed across all passenger locations. Quantitatively, the front passengers experienced an average SPL reduction of 3 dB, while the rear passengers showed an average decrease of 1 dB. These results indicate that the applied absorbing materials were most effective in the front region, particularly around the firewall area, where the primary leakage paths were previously identified.

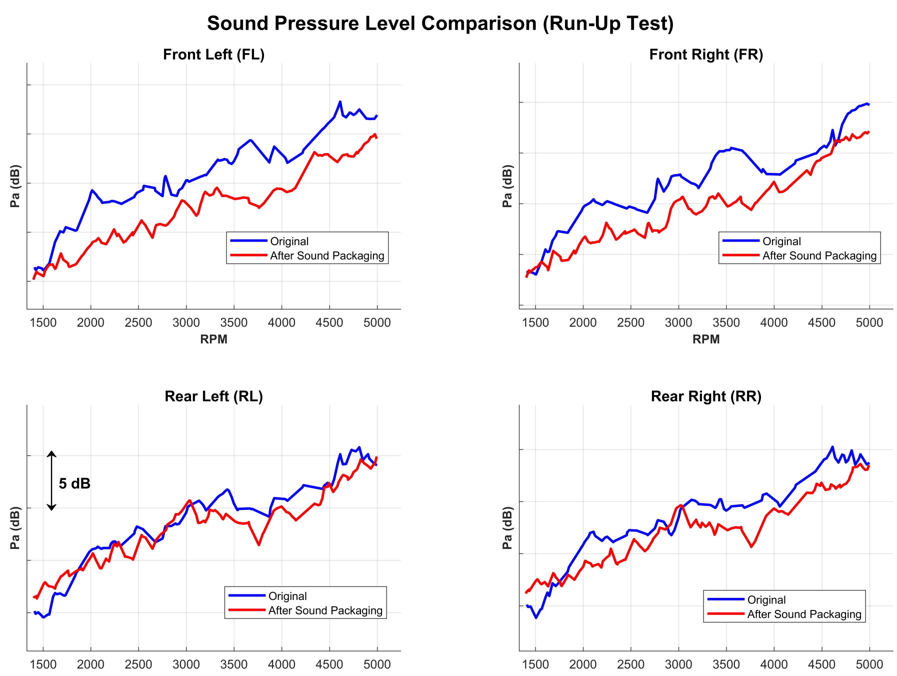


Figure 4. Interior SPL Results During Run-Up Test.

The more significant improvement observed for the front passengers, compared to the rear, can be directly attributed to the location of the applied sound insulation treatment. Since the acoustic countermeasures were primarily focused on the firewall—the primary barrier between the engine bay and the passenger cabin—they were most effective at mitigating the sound transmission paths directly affecting the front seating area. Consequently, the acoustic energy propagating from the engine side was more effectively attenuated before reaching the front passengers, leading to a greater measured reduction in SPL in that region.

4. Conclusion

This study presents a practical methodology for vehicle interior noise control using direct acoustic measurement and targeted treatment. The three-stage approach—leak detection via P-U probe mapping, strategic material application, and quantitative validation—effectively identifies and mitigates sound leakage paths without complex simulations. Experimental results demonstrate the method's efficacy, showing 3 dB SPL reduction for front passengers and 1 dB for rear passengers after treating critical firewall areas with polyurethane foam and EPDM rubber. The approach offers significant advantages in operational efficiency through single-probe scanning, objective visualization via acoustic color maps, and enhanced accuracy from vector-based measurements.

This work presents a practical, cost-effective, and repeatable alternative for vehicle NVH refinement. It provides engineering teams with a streamlined tool for rapid development cycles, enabling targeted improvements in cabin acoustic comfort without the need for extensive simulations or time-consuming traditional methods. Future work will focus on extending this methodology to a wider range of vehicle platforms and operational conditions, and on further optimizing the material selection and placement strategies for even greater weight and cost efficiency.

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